On the Early-time Kinetic Energy Profile for the Rayleigh-Taylor Instability

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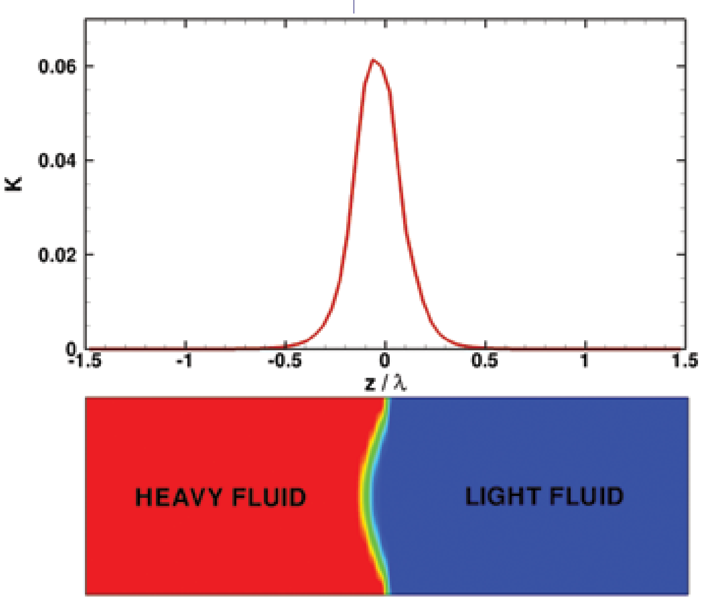
The Rayleigh-Taylor instability is an interfacial fluid instability that leads to turbulence and turbulent mixing. It occurs when a light fluid is accelerated into a heavy fluid [1,2] because of misalignment between density and pressure gradients. The Rayleigh-Taylor instability plays a key role in a wide variety of contexts such as supernovae explosions, salt dome formation, and oceanic flows, as well as in technological applications such as rotating machinery or in the implosion phase of inertial confinement fusion (ICF).

Traditional research in turbulence assumes that turbulent flows have no memory of the initial conditions, and turbulence develops to a universal self-similar state. However, recent research has shown that initial conditions are of great importance during the growth of the turbulent Rayleigh-Taylor instability [3,4]. As a result, the need for accurate initial conditions in turbulence models has now become clear.

Fig. 1. Top: kinetic energy profile soon after the beginning of the nonlinear growth. K: kinetic energy; λ: wavelength of the initial perturbation. Bottom: interface profile. A_T=0.5.



Kinetic energy is a fundamental parameter in most common turbulence models. In this work, our objective was to study the early-time evolution of the kinetic energy profile in the case of a single-mode initial perturbation. It is indeed important to have a good description of this basic case, since most of the complex models describing the multimode turbulent instability are built on a single-mode model (c.f., Fourier decomposition).

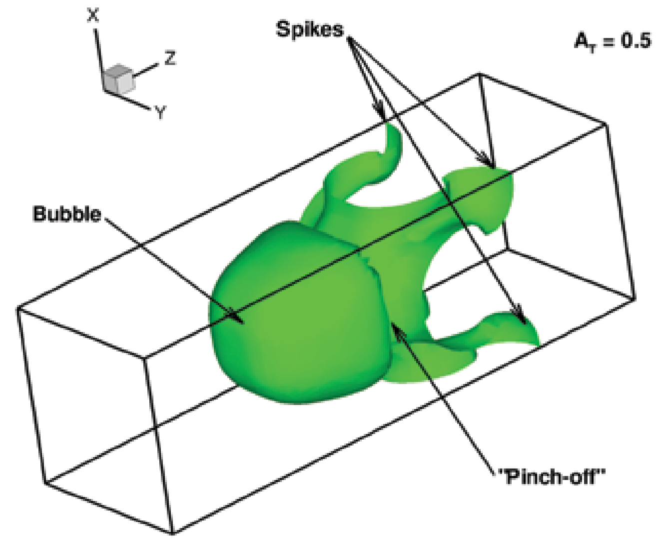


Fig. 2. Interface between the heavy and light fluid at A_T=0.5.

Simulations of a single-mode initial perturbation at low, intermediate, and large Atwood numbers (density contrast) were performed using an incompressible MILES code [5], RTI3D. During the linear and early nonlinear stage of the instability, the kinetic energy profile is simple as the flow remains relatively symmetrical (Fig. 1), and reflects the sinusoidal nature of the perturbation. We observe a peak of kinetic energy located around the centerline of the initial sine perturbation. The profile prediction during the linear (actually exponential growth phase) is then straightforward using velocity predictions from theoretical models. Figure 2 shows a typical shape of the interface (computed using RTI3D) between the heavy and the light fluid after some time in the nonlinear regime ($h_B/\lambda \sim 0.6$, where h_B is the height of the bubble). The bubble (blob of light rising into the heavy fluid) is now well formed. The vortices on the spikes (blobs of heavy fluid falling into the light fluid) side are well developed, and we observe a pinch-off region at about the centerline. At this stage of the nonlinear regime, theoretical models are still able to provide a good estimate of the position of the tips of the bubbles and the spikes at low and intermediate Atwood numbers [6]. However, there are to the authors' knowledge no models predicting the velocity distribution in the mixing region, and hence no model to predict the kinetic energy profile. The kinetic energy profile from RTI3D is displayed on the bottom pictures of Fig. 3 for different Atwood numbers, and the shape of the instability colored by the instantaneous kinetic energy is displayed on the top pictures. All profiles show two local maxima corresponding to the vortices located at the pinch-off and near the tip of the spikes. However, if the instantaneous kinetic energy is higher near the spikes (top row Fig. 3), the azimuthally averaged kinetic energy (bottom row Fig. 3) displays a higher value in the pinch-off region, which occupies a larger volume. As the Atwood number increases, the asymmetry between spikes and bubbles increases. For larger Atwood number, the intensity of the vortices is more inhibited by the density contrast, resulting in a smaller value of kinetic energy. Figure 4 shows that the local maxima in the kinetic energy profile are mainly due to the contribution of the vortex ring of the pinch-off region and the smaller vortex rings located near the tip of the spikes. The observations made in this work will provide us with guidance for deriving a model for kinetic energy profile prediction at early-time for the turbulent Rayleigh-Taylor instability.

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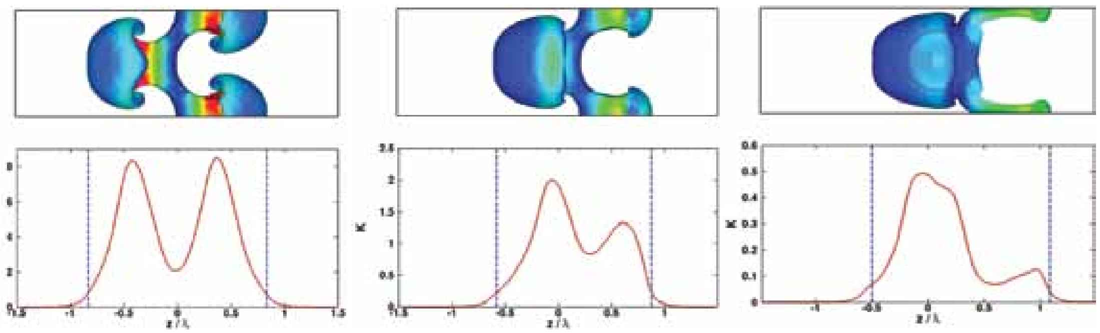

Fig. 3. Top: View in the xz-plane of the interface between the heavy and the light fluid. Bottom: kinetic energy profile (red). The dashed blue lines indicate the position of the tips of the bubble and spikes. A_T=0.0 (left); A_T=0.5 (middle); A_T=0.9 (right).

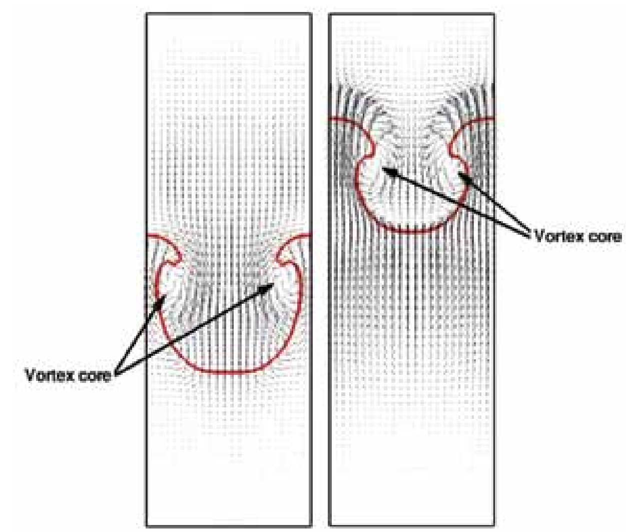

Fig. 4. Slice of the velocity distribution in the mid-plane y = λ/2 (left) and the plane y=0 (right). The interface is represented by the red line.

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